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Higgs phenomenology in the minimal $B - L$ extension of the Standard Model at LHC

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Abstract

We present some phenomenology of the Higgs sector of the Minimal $B - L\ U(1)$ Extension of the Standard Model at the Large Hadron Collider. In this model, the existence of an extra gauge boson (Z') and an extra scalar (heavy Higgs) are predicted as naturally related with the breaking of the $B - L$ (baryon minus lepton number) symmetry. For this, we have started by deriving the unitarity bounds in the high energy limit for the Minimal $B - L$ Model parameter space. This was accomplished by analysing the full class of Higgs and would-be Goldstone boson two-to-two scatterings at tree level (exploiting the Equivalence Theorem). Hence, we studied some peculiar signature that could be observed at the CERN machine in the search of both light and heavy Higgs bosons.

1   Introduction

Despite there is no experimental evidence of a Higgs boson, the Higgs mechanism is still considered one of the favourite means for generating the masses of particles.

In the Standard Model (SM) framework this mechanism is realised by one Higgs doublet consisting of four degrees of freedom, three of which, after spontaneous Electro-Weak Symmetry Breaking (EWSB), turn out to be absorbed in the longitudinal polarisation component of each of the three weak gauge bosons, $W^{\pm}$ and Z, while the fourth one gives the physical Higgs state h.

It is clear that the SM represents a minimal choice that is completely arbitrary (as far as we know), and in the past years a big effort has been devoted to explore the implication of more complicated Higgs models, both in the context of the SM and in Beyond the Standard Model (BSM) extended theories.

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[1]Speaker

One of the possible BSM scenarios is the minimal $B-L$ (Barion minus Lepton number) gauge extension of the SM, which has been recently explored (see [1]) as one of the candidates in the description of a rather simple phenomenological framework.

This model has an augmented $B-L$ gauge symmetry, that results in the natural presence of a new vector boson Z', a new Higgs field (related to the $B-L$ symmetry breaking) and, in order to preserve the theory from anomalies, one right-handed neutrino field per fermionic family (related to three heavy neutrinos as particle contents of the model).

In the present work we present a brief analysis of the phenomenology of the $B-L$ Higgs sector at the Large Hadron Collider (LHC), with emphasis on one distinctive signature of the model: the heavy neutrino pair production mediated by a light Higgs in proton-proton collision.

Firstly, in order to give a consistent picture of the allowed parameter space of the Higgs sector, we will briefly present the results of Reference [2, 3] where the Higgs parameter space of the minimal $B-L$ model was studied in detail by accounting for both experimental and theoretical constraints.

Thereafter, we will present the production cross-sections and Branching Ratios (BRs), in order to use these results to introduce some peculiar Higgs signatures at the LHC that are not allowed by the SM assumption, and therefore they could be the hallmark of the $B-L$ model.

2   The Model

The model under study is the so-called "pure" or "minimal" $B-L$ model because of the vanishing mixing between the two $U(1)_Y$ and $U(1)_{B-L}$ groups. In this model the classical gauge invariant Lagrangian, obeying the $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ gauge symmetry, can be decomposed as:

$$\mathscr{L} = \mathscr{L}_{YM} + \mathscr{L}_s + \mathscr{L}_f + \mathscr{L}_Y. \tag{1}$$

The non-Abelian field strengths in $\mathscr{L}_{YM}$ are the same as in the SM whereas the Abelian ones can be intuitively identified. In this field basis, the co-variant derivative is: $D_\mu \equiv \partial_\mu + ig_S T^\alpha G_\mu{}^\alpha + ig T^a W_\mu{}^a + ig_1 Y B_\mu + i(\widetilde{g} Y + g_1' Y_{B-L}) B_\mu'$. The "pure" or "minimal" $B-L$ model is defined by the condition $\widetilde{g}(EW) = 0$, that implies no mixing between the Z' and the SM-Z gauge bosons at the tree-level at the EW scale.

The fermionic Lagrangian is the usual SM one, apart from the presence of Right-Handed (RH) neutrinos. The charges are the usual SM and $B-L$ ones (in particular, $B-L = 1/3$ for quarks and -1 for leptons). The $B-L$ charge assignments of the fields as well as the introduction of new fermionic RH-neutrinos (ν_R) and scalar Higgs (χ, charged $+2$ under $B-L$) fields are designed to eliminate the triangular $B-L$ gauge

anomalies and to ensure the gauge invariance of the theory, respectively. Therefore, the $B - L$ gauge extension of the SM group broken at the Electro-Weak (EW) scale does necessarily require at least one new scalar field and three new fermionic fields which are charged with respect to the $B - L$ group.

The scalar Lagrangian is:

$$\mathscr{L}_s = (D^\mu H)^\dagger D_\mu H + (D^\mu \chi)^\dagger D_\mu \chi - V(H, \chi), \tag{2}$$

with the scalar potential given by

$$V(H, \chi) = m^2 H^\dagger H + \mu^2 \mid \chi \mid^2 + \lambda_1 (H^\dagger H)^2 + \lambda_2 \mid \chi \mid^4 + \lambda_3 H^\dagger H \mid \chi \mid^2, \tag{3}$$

where H and χ are the complex scalar Higgs doublet and singlet fields, respectively.

From this potential, with standard algebraic manipulation (see [2]), one finds the explicit expressions for the Higgs bosons masses and mixing angle in terms of λ parameters.

Being h_1 and h_2 the scalar fields with masses m_{h_1} and m_{h_2} respectively (we conventionally choose $m_{h_1}^2 < m_{h_2}^2$), we give the explicit expressions for the scalar mass eigenvalues:

$$m_{h_1}^2 = \lambda_1 v^2 + \lambda_2 x^2 - \sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}, \tag{4}$$
$$m_{h_2}^2 = \lambda_1 v^2 + \lambda_2 x^2 + \sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}, \tag{5}$$

and eigenvectors:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ h' \end{pmatrix}, \tag{6}$$

where $-\frac{\pi}{2} \leq \alpha \leq \frac{\pi}{2}$ fulfils:

$$\sin 2\alpha = \frac{\lambda_3 x v}{\sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}}. \tag{7}$$

Finally, the Yukawa interactions are: $\mathscr{L}_Y = -y_{jk}^d \overline{q_{jL}} d_{kR} H - y_{jk}^u \overline{q_{jL}} u_{kR} \widetilde{H} - y_{jk}^e \overline{l_{jL}} e_{kR} H - y_{jk}^\nu \overline{l_{jL}} \nu_{kR} \widetilde{H} - y_{jk}^M \overline{(\nu_R)_j^c} \nu_{kR} \chi + \text{h.c.}$, where $\tilde{H} = i\sigma^2 H^*$ and i, j, k take the values 1 to 3, where the last term is the Majorana contribution and the others the usual Dirac ones.

3   Results

Firstly, we have made an extensive study on the Higgs-sector parameter-space allowed by theoretical constraints exploiting the well-known techniques from consideration on vacuum stability and triviality (renormalisation group equations (RGEs) techniques, see [3]) and perturbative unitarity (PU) (see [2]). The latter, in particular, is not energy-scale dependent, and it results in a simpler description of the $m_{h_1} - m_{h_2} - \alpha$ allowed space, and we will mainly consider it in the following analysis.

By analysing the full class of Higgs and would-be Goldstone boson two-to-two scatterings at tree level (exploiting the Equivalence Theorem) one finds the following result: the theory is PU-stable if $m_{h_1} < 700$ GeV and

$$m_{h_2} < 2\sqrt{\frac{2}{3}} \, \min\left(\frac{m_W}{\sqrt{\alpha_W} \sin\alpha}, \sqrt{\pi}x\right),$$ (8)

where $\alpha_W = \alpha_{em}/\sin^2\theta_W$.

Considering the experimental limits from LEP (which established that the safest choice for the light Higgs boson mass is $m_{h_1} > 115$ GeV) we have a complete definition of the allowed Higgs-sector parameter space.

For completeness, we have also combined the RGEs and PU techniques in order to find a dynamical constraint on the g_1' domain (see [4]). From this method, assuming that the $B - L$ symmetry breaking occurs at the TeV scale, one finds that the model is PU-stable to the Planck scale only if $g_1' < 0.23$.

Thereafter, we have analysed the production mechanism channels both for h_1 and h_2 in proton-proton colliders, with emphasis on two LHC energy-luminosity configurations: "early discovery scenario" with $\sqrt{s} = 7$ GeV and $L = 1$ fb^{-1}, "full integrated luminosity" scenario with $\sqrt{s} = 14$ GeV and $L = 300$ fb^{-1}.

As explicit example, in figure 1 we show the full set of production mechanisms for h_1 in proton-proton collision at $\sqrt{s} = 7$ GeV for $\alpha = \pi/5$: as in the SM case, the dominant mode is represented by the gluon-gluon fusion (black line) process, while the inclusive processes as vector boson fusion (VBF) (red line), the H-strahlung processes (blue line for $W^{\pm}$ and violet line for Z) and the associated production of top and Higgs (green line) represent a significantly smaller contribution. For completeness, we have superimposed the SM-like case ($\alpha = 0$) in dotted lines.

Besides, we have evaluated the BRs both for h_1 and h_2, in the search for configurations in which it could be possible to have any peculiar signature of the model.

Considering the h_1-decay, we have analysed the role that a "light" heavy neutrino mass ($m_Z/2 < m_{\nu_h} < m_W$) could play in the BRs, in order to establish if such decaying-channel could be visible in the early discovery scenario at LHC. In particular, in figure 2 we plot the Branching ratio for $h_1 \to 2\nu_h$ (summing over the three generation of heavy neutrinos) against the light Higgs boson mass m_{h_1} for $\nu_h = 50$ GeV[2] and several values of the mixing angle α in units of $\pi/2$: $\alpha = 0.2$ (blue line), $\alpha = 0.4$ (green line), $\alpha = 0.6$ (red line), $\alpha = 0.8$ (black line).

Considering the h_2-decay, instead, we have analysed how the presence of a "light" Z'-boson (the $m_{Z'} = 210$ GeV choice forces us to choose $g_1' < 0.03$ because of the LEP limits, see [5]) could affect the BRs, in order to establish if such decaying-channel could

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[2]We assume that the three heavy neutrinos mass eigenstates are degenerate as this does not affect our analysis.

be visible in the full integrated luminosity scenario at LHC. Nevertheless, we have also studied the role of a light Higgs boson ($m_{h_1} = 120$ GeV) in the h_2's BRs, because of the fact that the channel $h_2 \to 2h_1$ represents a peculiar signature of the model, that is distinctive with respect to supersymmetrical Models in which the mixing in the scalar sector is forbidden.
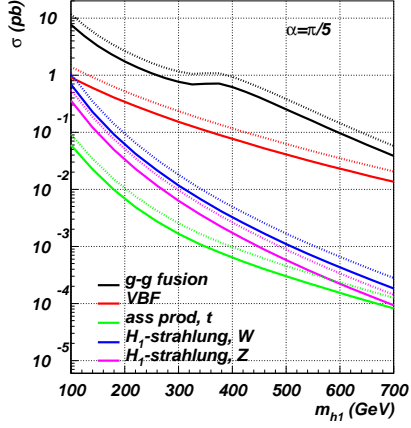

Figure 1: Cross-section for h_1 production at LHC ($\sqrt{s} = 7$ TeV) plotted against the light Higgs boson mass m_{h_1} at $\alpha = \pi/5$ in g-g fusion (black line), VBF (red line), Higgs-strahlung from $W^\pm$ (blue line) and Z (violet line) and associated production with top (green line). The SM-like case has been superimposed in dotted lines.
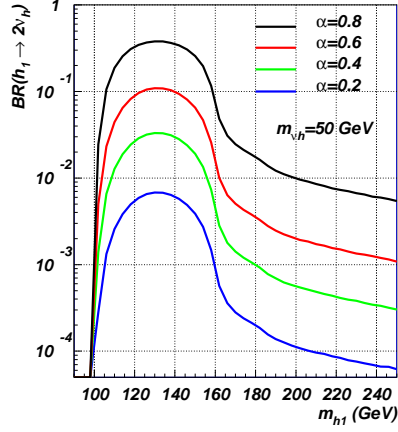
Figure 2: Branching ratio for the light Higgs boson decaying in two heavy neutrinos ($h_1 \to 2\nu_h$) in the minimal $B - L$ model plotted against the light Higgs boson mass m_{h_1} for $\nu_h = 50$ GeV and several values of the mixing angle α in units of $\pi/2$: $\alpha = 0.2$ (blue line), $\alpha = 0.4$ (green line), $\alpha = 0.6$ (red line), $\alpha = 0.8$ (black line).

Finally, by combining the two analysis (Higgses productions and BRs), we have made a detailed study of the cross-section for some peculiar signature of the model: $pp \to h_1 \to \nu_h\nu_h$, $pp \to h_2 \to h_1h_1$ and $pp \to h_2 \to Z'Z'$. The analysis of each of these processes has shown how there is the possibility to observe such signatures both in the early discovery scenario ($pp \to \nu_h\nu_h$) and in the full integrated luminosity scenario ($pp \to h_1h_1$ and $pp \to Z'Z'$).

In particular, in figure 3 we show the explicit result for the $pp \to h_1 \to \nu_h\nu_h$ process at LHC with $\sqrt{s} = 7$ TeV and $m_{\nu_h} = 50$ GeV: a cross-section contour "sliced" in the m_{h_1}-α plane. Several values of the cross-section have been considered: $\sigma = 5$ fb (black line), $\sigma = 10$ fb (red line), $\sigma = 100$ fb (green line), $\sigma = 250$ fb (blue line). The red-shadowed region is excluded by the LEP experiments.

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Even if we consider a low-luminosity scenario ($L \simeq 1$ fb^{-1}), it is clear from the plot that there is a noticeable allowed parameter space for which the rate of events is considerably large: when the integrated luminosity reaches $L = 1$ fb^{-1} (that is equivalent to $18 - 24$ months of $\sqrt{s} = 7$ TeV running at LHC according to the official programme) we estimated a collection of ~ 10 heavy neutrino pair productions for 100 GeV$< m_{h_1} < 165$ GeV and $0.05\pi < \alpha < 0.48\pi$, that scales up to $\sim 10^2$ events for 110 GeV$< m_{h_1} < 150$ GeV and $0.15\pi < \alpha < 0.46\pi$.

This represents a clear chance to establish a heavy neutrino discovery within the next two years at the CERN machine.
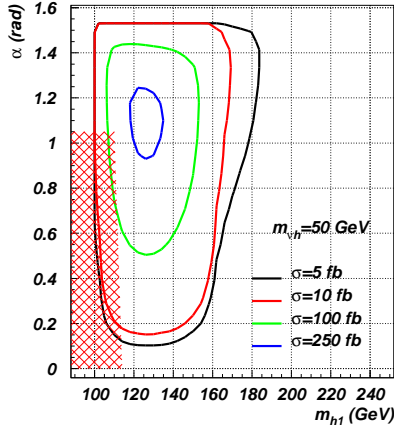

Figure 3: Cross-section contour plot for the process $pp \rightarrow h_1 \rightarrow \nu_h \nu_h$ at LHC $\sqrt{s} = 7$ TeV, plotted against m_{h_1}-α, with $m_{\nu_h} = 50$ GeV. Several values of the cross-section have been considered: $\sigma = 5$ fb (black line), $\sigma = 10$ fb (red line), $\sigma = 100$ fb (green line), $\sigma = 250$ fb (blue line). The red-shadowed region is excluded by the LEP experiments.

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